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ROBUST AGC IN A COMPETITIVE ENVIRONMENT

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ABSTRACT

A decentralized robust approach is proposed for the Automatic Generation Control (AGC) system based on a generalized AGC structure. This work addresses a new strategy to adapt well-tested classical AGC scheme to the changing environment of power system operation under deregulation. The effect of bilateral contracts is taken into account in each control area dynamical model as a set of new input signals. In this paper, the PI-based AGC synthesis is formulated via an H∞ static output control problem and is solved using an iterative linear matrix inequalities (ILMI) algorithm. A three area power system example with possible contract scenarios and wide range of load changes is given to illustrate the proposed approach. The resulting controllers are shown to minimize the effect of disturbances and maintain the robust performance.

Keywords: Automatic generation control, H∞ control, restructured power system, linear matrix inequalities

INTRODUCTION

Automatic Generation Control (AGC) as an ancillary service acquires a fundamental role in restructured power system for maintaining the electrical system reliability at an adequate level. That is why there has been increasing interest for AGC synthesis with better performance during past years and for this purpose many optimal and robust control strategies have been developed. But the most of them suggest complex state-feedback or high-order dynamic controllers, which are not practical for industry practices. Furthermore, some references have used the new and untested AGC frameworks, which may have some difficulties to implement in real-world power systems. Usually, the existing AGC systems in the practical power systems use the proportional-integral (PI) type controllers that are tuned online based on experiences or trial-and-error approaches. A PI control design method is reported in [1], which has used a combination of H∞ control and genetic algorithm techniques for tuning the PI parameters. [2] has given an iterative linear matrix inequalities (ILMI) algorithm for the same purpose, but both of them refer to traditional AGC structures.

Recently, several reported strategies have addressed the well tested classical AGC schemes corresponding to power system operation under deregulation. A generalized dynamical model for a given control area in a deregulated environment is introduced in [3], following the idea presented in [4] for a 2-control area power system. This model shows how the bilateral contracts are incorporated in the traditional LFC system leading to a new model.

In this paper, using the given results in [3], the AGC problem in a bilateral-based deregulated environment is formulated as a standard H∞ control problem to obtain the proportional-integral (PI) controller via a static output feedback design. An iterative linear matrix inequalities (ILMI) algorithm is used to compute PI parameters. The proposed strategy is applied to a three control area example. The obtained robust PI controllers, which are ideally practical for industry, are compared with the H∞-based output dynamic feedback controllers (using general LMI technique). The results show the controllers guarantee the robust performance for a wide range of operating conditions as well as full-dynamic H∞ controllers.

AGC MODEL AND PROBLEM FORMULATION

Bilateral-based AGC structure

In the restructured power systems, the common objectives, i.e. restoring the frequency and the net interchanges to their desired values for each control area are remained. In [3], a traditional-based dynamical model is generalized for a given control area in deregulated environment under bilateral AGC scheme following the idea presented in [4]. The generalized AGC model uses all the information required in a vertically operated utility industry plus the contract data information.

Based on mentioned model, overall power system structure can be considered as a collection of distribution (Discos) or control areas interconnected through high voltage transmission lines. Each control area has its own AGC and is responsible for tracking its own load and honoring tie-line power exchange contracts with its neighbors. There can be various combinations of contracts between each Disco and available Gencos. On the other hand each Genco can contract with various Discos. The "generation participation matrix (*GPM*)" concept is defined to express these bilateral contracts in the generalized model (similar to *DPM* concept in [4]). *GPM* shows the participation factor of each Genco in the considered control areas and each control area is determined by a Disco. The rows of a *GPM* correspond to Gencos and columns to control areas which contract power. For example, for a large scale power system with m control area (Discos) and n Gencos, the GPM will have the following structure. Where gpf_{ij} refers to "generation participation factor" and shows the participation factor of Genco i in the load following of area j (based on a specified bilateral contract).

$$GPM = \begin{bmatrix} gpf_{11} & gpf_{12} & \cdots & gpf_{1(m-1)} & gpf_{1m} \\ gpf_{21} & gpf_{22} & \cdots & gpf_{2(m-1)} & gpf_{2m} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ gpf_{(n-1)1} & gpf_{(n-1)2} & \cdots & gpf_{(n-1)(m-1)} & gpf_{(n-1)m} \\ gpf_{n1} & gpf_{n2} & \cdots & gpf_{n(m-1)} & gpf_{nm} \end{bmatrix}$$

The generalized AGC block diagram for control area i can be obtained in a deregulated environment as shown in Fig. 1. New information signals due to possible various contracts between Disco i and other Discos and Gencos are shown as dashed-line inputs, and, we can write [3]:

$$\sum_{i=1}^{n} gpf_{ij} = 1 \tag{1}$$

$$\sum_{k=1}^{n} \alpha_{ki} = 1 \quad ; \quad 0 \le \alpha_{ki} \le 1 \tag{2}$$

$$\Delta P_{mi} = \sum_{j=1}^{N} gpf_{ij} \Delta P_{Lj} \tag{3}$$

$$w_{1i} = \Delta P_{Loc-i} + \Delta P_{di} \tag{4}$$

$$\begin{aligned} w_{3i} &= \sum (\text{Total export power} - \text{Total import power}) \\ &= \sum_{\substack{j=1 \\ j\neq i}}^{N} \Big(\sum_{k=1}^{n} gpf_{kj}\Big)\Delta P_{Lj} - \sum_{k=1}^{n}\Big(\sum_{\substack{j=1 \\ j\neq i}}^{N} gpf_{jk}\Big)\Delta P_{Li} \end{aligned} \tag{5}$$

$$\Delta P_{tie-i,error} = \Delta P_{tie-i,actual} - w_{3i} \tag{6}$$

$$\begin{aligned} w_{4i-1} &= \sum_{j=1}^{N} gpf_{1j} \Delta P_{Lj} \\ &\vdots \\ w_{4i-n} &= \sum_{j=1}^{N} gpf_{nj} \Delta P_{Lj} \end{aligned} \tag{7}$$

where, Δf_i: frequency deviation, ΔP_{gi}: governor valve position, ΔP_{ci}: governor load setpoint, ΔP_{ti}: turbine power, ΔP_{tie-i}: net tie-line power flow, ΔP_{di}: area load disturbance, M_i: equivalent inertia constant, D_i: equivalent damping coefficient, T_{gi}: governor time constant, T_{ti}: turbine time constant, T_{ij}: tie-line synchronizing coefficient between area i & j, B_i: frequency bias, R_i: drooping characteristic, α: ACE participation factor, N: number of control areas, ΔP_j: *pu* demand of area j, ΔP_{mi}: power generation of a Genco i, ΔP_{Loc-i}: contracted local demand, w_{3i}: scheduled ΔP_{tie-i} ($\Delta P_{tie-i,scheduled}$), and $\Delta P_{tie-i,actual}$: actual ΔP_{tie-i}.

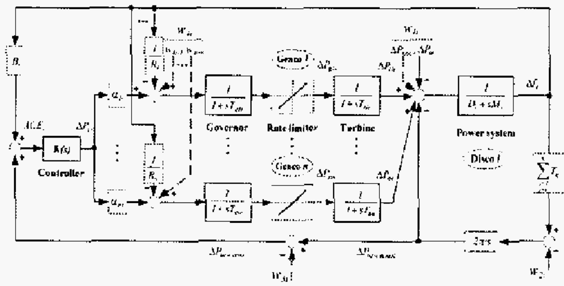

Figure 1. Control area model for a deregulated environment.

Problem formulation

A large scale power system consists of a number of interconnected distribution control areas; each control area has a Disco and several Gencos. As shown in Fig. 1, the ACE performs the input signal of controller:

$$u_i = \Delta Pci = k_{Pi} ACE_i + k_{Ii} \int ACE_i \tag{8}$$

In order to change (8) to a simple static feedback control as

$$u_i = K_i y_i \tag{9}$$

We can rewrite (8) as follows, [1]:

$$u_i = [k_{Pi} \quad k_{Ii}] \begin{bmatrix} ACE_i \\ \int ACE_i \end{bmatrix} \tag{10}$$

The main control framework in order to formulation the PI-based AGC via a static output H∞ controller design problem for a given control area is shown in Fig. 2. $G_i(s)$ denotes the dynamical model corresponding to the modified control area (Fig. 1). w_i, u_i, y_i and z_i are disturbances and other external input vector, control input, controlled output vector and measured output vector, respectively. The η_{1i}, η_{2i} and η_{3i} are constant weighting coefficients that must be chosen by the designer to get the desired performance.

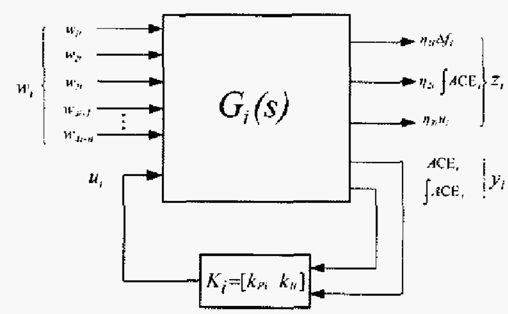

Figure 2. Proposed control framework

According to Fig. 2, consider the following state space model for each control area:

$$\begin{aligned} \dot{x}_i &= A_i x_i + B_{1i} w_i + B_{2i} u_i \\ z_i &= C_{1i} x_i + D_{12i} u_i \\ y_i &= C_{2i} x_i \end{aligned} \tag{11}$$

where

$$x_i^T = [\Delta f_i \quad \Delta P_{tie-i} \quad \int ACE_i \quad x_{ti} \quad x_{gi}]$$

$$x_{ti} = [\Delta P_{t1i} \quad \Delta P_{t2i} \quad \cdots \quad \Delta P_{tni}]$$

$$x_{gi} = [\Delta P_{g1i} \quad \Delta P_{g2i} \quad \cdots \quad \Delta P_{gni}]$$

$$y_i^T = [ACE_i \quad \int ACE_i], \quad u_i = \Delta P_{Ci}$$

$$z_i^T = [\eta_{1i}\Delta f_i \quad \eta_{2i}\int ACE_i \quad \eta_{3i} u_i]$$

$$w_i^T = [w_{1i} \quad w_{2i} \quad w_{3i} \quad w_{4i}]$$

$$w_{4i}^T = [w_{4i-1} \quad w_{4i-2} \quad \cdots \quad w_{4i-n}]$$

PROPOSED ILMI ALGORITHM

H∞ static output control problem can be easily reduced to a generalized static output stabilization feedback control problem. Using this key point an iterative LMI algorithm (which is mainly based on given approach in [5]) is developed. The proposed algorithm gives an LMI-based solution for the following optimization problem: Given an optimal performance index γ, determine an admissible static output feedback law

$$u_i = K_i y_i \ , \quad K_i \in K_{sof} \tag{12}$$

such that

$$\|T_{zi\,wi}(s)\|_\infty < \gamma^* \tag{13}$$

where K_{sof} is a family of internally stabilizing static output feedback gains and γ^* indicates a lower bound such that the closed-loop system is H∞ stabilizable via static output feedback. In this case we could see that $|\gamma - \gamma^*| < \varepsilon$, where ε is a small positive number. The following algorithm gives an iterative LMI solution for above optimization problem [2]:

Step 1. Compute a generalized system $(\overline{A}, \overline{B}, \overline{C})$ using (11),

$$\overline{A} = \begin{bmatrix} A_i & B_{1i} & 0 \\ 0 & -\gamma I/2 & 0 \\ C_{1i} & 0 & -\gamma I/2 \end{bmatrix}, \quad \overline{B} = \begin{bmatrix} B_{2i} \\ 0 \\ D_{12i} \end{bmatrix}, \quad \overline{C} = [C_{2i} \quad 0 \quad 0]$$

Set $i = 1$, $\Delta\gamma = \Delta\gamma_0$ and let $\gamma_i = \gamma_0 > \gamma$. $\Delta\gamma_0$ and γ_0 are positive real numbers.

Step 2. Select $Q > 0$, and solve $\overline{X}$ from the following algebraic Riccati equation

$$\overline{A}^T \overline{X} + \overline{XA} - \overline{XBB}^T \overline{X} + Q = 0 \tag{14}$$

Set $P_1 = \overline{X}$.

Step 3. Solve the following optimization problem for $\overline{X}_i$, K_i and a_i.
Minimize a_i subject to the bellow LMI constraints:

$$\begin{bmatrix} \overline{A}^T \overline{X}_i + \overline{X}_i \overline{A} - P_i \overline{BB}^T \overline{X}_i - \overline{X}_i \overline{BB}^T P_i + P_i \overline{BB}^T P_i - a_i \overline{X}_i & (\overline{B}^T \overline{X}_i + K_i \overline{C})^T \\ \overline{B}^T \overline{X}_i + K_i \overline{C} & -I \end{bmatrix} < 0 \tag{15}$$

$$\overline{X}_i = \overline{X}_i^T > 0. \tag{16}$$

Denote a_i^* as the minimized value of a_i.

Step 4. If $a_i^* \le 0$, go to step 8.

Step 5. For $i > 1$ if $a_{i-1}^* \le 0$, $K_{i-1} \in K_{sof}$ and it is desired H∞ controller and $\gamma^* = \gamma_i + \Delta\gamma$ indicates a lower bound such that the above system is H∞ stabilizable via static output feedback.

Step 6. Solve the following optimization problem for $\overline{X}_i$ and K_i:
Minimize trace($\overline{X}_i$) subject to the above LMI constraints (15-16) with $a_i = a_i^*$. Denote $\overline{X}_i^*$ as the $\overline{X}_i$ that minimized trace($\overline{X}_i$).
Step 7. Set $i = i+1$ and $P_i = \overline{X}_{i-1}^*$, then go to step 3.

Step 8. Set $\gamma_i = \gamma_i - \Delta\gamma$, $i = i+1$. Then do steps 2 to 4.

CASE STUDY

To illustrate the effectiveness of proposed control strategy, a three control area power system shown in Fig. 3, is considered as a test system. It is assumed that each control area includes two Gencos and one Disco. The power system parameters are assumed the same as [6].

For the sake of comparison, in addition to proposed control strategy to obtain the robust PI controller, a robust H∞ dynamic output feedback controller using LMI control toolbox [7] has been designed for each area. The optimal H∞ dynamic controller is resulted through the minimizing the guaranteed robust performance index subject to the constraints given by the matrix inequalities and returns the controller $K(s)$ with optimal robust performance index. Here, a set of suitable constant weights η_{1i}, η_{2i} and η_{3i} are chosen as 5, 0.5 and 400, respectively. The resulted controllers are dynamic type, whose orders are the same as size of area model (7 order). At the next step, according to described synthesis methodology, a set of three decentralized robust PI controllers are designed. Using ILMI approach, the controllers are obtained following several iterations. The resulted control parameters are shown in table 1. γ^* indicates the upper bound such that the control area is H∞ stabilizable via static output feedback.

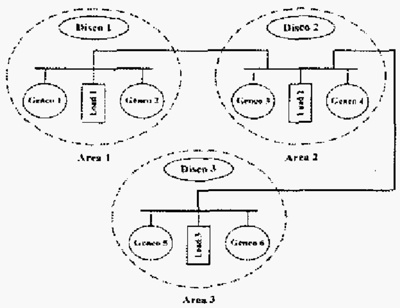

Figure 3. Three control area power system

Table 1. Control parameters from ILMI algorithm

Parameters	*Area 1*	*Area 2*	*Area 3*
σ^*	-0.3901	-0.2610	-0.0407
γ^*	803.0396	801.0306	800.8762
k_{Pi}	-0.2695	-0.0418	-0.2319
k_{Ii}	-0.3788	-0.1806	-0.3796

SIMULATION RESULTS

In order to demonstrate the effectiveness of the proposed strategy, some simulations were carried out. In these simulations, the proposed controllers were applied to the three control area power system described in Fig. 3. The performance of the closed-loop system using the robust PI controllers in comparison of full order dynamic H∞ controllers is tested for the various possible scenarios of bilateral contracts and load disturbances.

Scenario 1:

A large load disturbance (a step increase in demand) is applied to each area:

$\Delta P_{L1} = 100\ MW,\ \Delta P_{L2} = 70\ MW,\ \Delta P_{L3} = 60\ MW$

Assume each Disco demand is sent to its local Gencos only, based on following GPM,

$$GPM = \begin{bmatrix} 0.5 & 0 & 0 \\ 0.5 & 0 & 0 \\ 0 & 0.5 & 0 \\ 0 & 0.5 & 0 \\ 0 & 0 & 0.5 \\ 0 & 0 & 0.5 \end{bmatrix}$$

Frequency deviation (Δf), power tie-line changes ($\Delta Ptie$), power changes (ΔPm), area control error (ACE) and its integral for closed-loop system are shown in Fig. 4 to Fig. 6. Using the proposed method (ILMI), the area control error and frequency deviation of all areas are quickly driven back to zero, the generated power and tie-line power are properly convergence to specified values, as well as dynamic H∞ control (LMI). As shown in these figures, the actual generated powers of Gencos, according to (3), reach the desired values in the steady state.

$$\Delta P_{m1} = gpf_{11}\Delta P_{L1} + gpf_{12}\Delta P_{L2} + gpf_{13}\Delta P_{L3}$$
$$= 0.5(0.1) + 0 + 0 = 0.05\ pu$$
$$\Delta P_{m2} = 0.05\ pu, \Delta P_{m3} = \Delta P_{m4} = 0.035\ pu,$$
$$\Delta P_{m5} = \Delta P_{m6} = 0.03\ pu$$

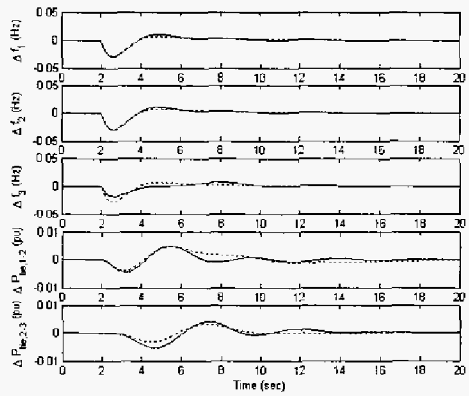

Figure 4. Δf and $\Delta Ptie$; solid (ILMI), dotted (LMI).

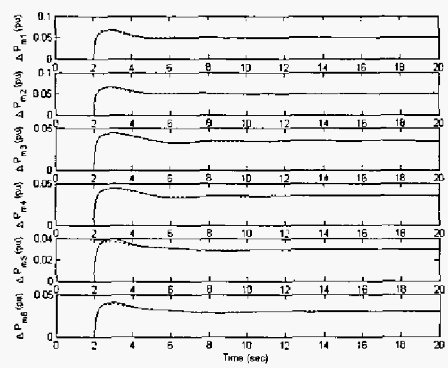

Figure 5. Power changes; solid (ILMI), dotted (LMI).

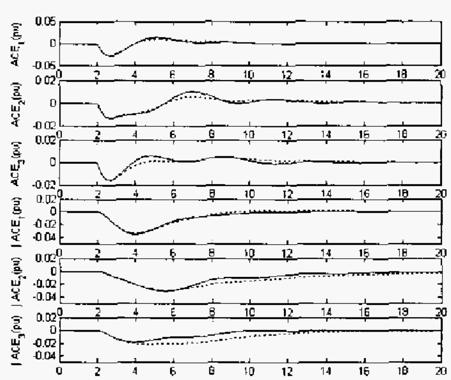

Figure 6. ACE and its integral; solid (ILMI), dotted (LMI).

Scenario 2:

Consider larger demands by Disco 2 and Disco 3 (100 MW) and assume Discos contract with the available Gencos in other areas, according to the following GPM,

$$GPM = \begin{bmatrix} 0.25 & 0.25 & 0 \\ 0.5 & 0 & 0 \\ 0 & 0.25 & 0.75 \\ 0.25 & 0.25 & 0 \\ 0 & 0.25 & 0 \\ 0 & 0 & 0.25 \end{bmatrix}$$

The closed-loop response is shown in Figs. 7 and 8. According to equation (3), the actual generated powers of Gencos for this scenario can be obtained as

$$\Delta P_{m1} = 0.25(0.1) + 0.25(0.1) + 0 = 0.05\ pu$$
$$\Delta P_{m2} = 0.05\ pu, \Delta P_{m3} = 0.1\ pu$$
$$\Delta P_{m4} = 0.05\ pu, \Delta P_{m5} = \Delta P_{m6} = 0.025\ pu$$

The simulation results show the same values in steady state. The scheduled power tie-lines in the directions from area 1 to area 2 and area 2 to area 3, using equation (5) are obtained as,

$$\Delta P_{tie,1\text{-}2} = (gpf_{12} + gpf_{22})\Delta P_{L2} - (gpf_{31} + gpf_{41})\Delta P_{L1}$$
$$= (0.25 + 0)0.1 - (0 + 0.25)0.1 = 0\ pu$$
$$\Delta P_{tie,2\text{-}3} = (0.75 + 0)0.1 - (0.25 + 0)0.1 = 0.05\ pu$$

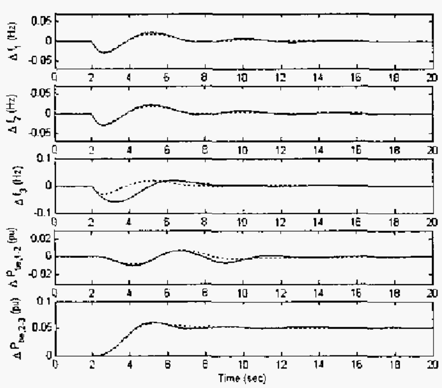

Figure 7. Δf and $\Delta Ptie$; solid (ILMI), dotted (LMI).

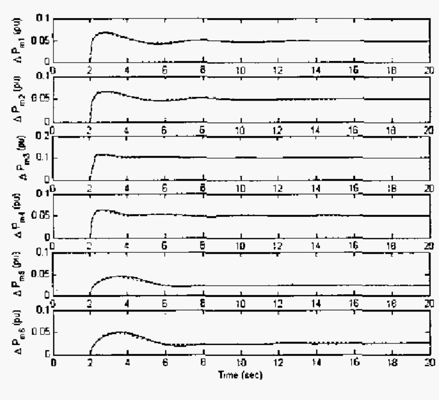

Figure 8. Power changes; solid (ILMI), dotted (LMI).

Fig. 7 shows actual tie-line powers and they reach to the calculated values at steady state. The simulation results show the proposed PI controllers perform robust performance as well as full order dynamic H∞ controllers (with complex structures) for a wide range of load disturbances and possible bilateral contract scenarios.

CONCLUSION

In this paper a new method for robust decentralized AGC design using an ILMI approach has been proposed for a generalized traditional AGC system model according to bilateral contracts in the restructured power system. Design strategy includes enough flexibility to meet the desired level of performance and gives a set of simple PI controllers via the H∞ static output control design, which commonly useful in real-world power systems. The proposed method was applied to a three control area power system. The results are compared with the results of applied dynamic H∞ output controllers. Simulation results demonstrated the effectiveness of synthesis methodology.

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